Surface Plasmon Tunable Filter for Multiband Spectral Imaging

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ABSTRACT

The SSC San Diego Advanced Technology Branch and the Jet Propulsion Laboratory have been developing a novel technology that can be applied to multiband imaging. The surface plasmon tunable filter (SPTF) uses color-selective absorption by a surface plasmon at a metal-dielectric interface to achieve its optical selectivity. If an electro-optic material is used as the dielectric and a voltage is applied to change the surface plasmon resonance, the reflected light can be modulated, i.e., the photons at surface plasmon resonance will be absorbed and the photons out of the resonance will be totally reflected. Therefore, the applied voltage controls the reflection spectrum, and an electrically tunable color filter is formed. This paper details progress in developing SPTF technology as a replacement for discrete filters. This technology will allow multi-band or hyperspectral imaging with a single filter/camera system.

BACKGROUND

An important aspect of theater missile defense is the multiband spectral characterization of plume radiation during the boost phase of a missile. Current Ballistic Missile Defense Organization (BMDO) plans call for study of the utility of a dual-mode ultraviolet (UV) and mid-wave infrared (MWIR) seeker. Combining the conventional MWIR sensor with shorter wavelengths provides increased information content for the image and can aid in optical target characterization. However, even dual-mode seekers have potential problems. Onboard optical seekers are subject to some vehicle self-interference. Sources of optical interference include out-gassing of vehicle contaminants, and by-products of the vehicle plume and attitude control systems, especially if solid aluminized propellants are used. Carbon particles are commonly present in the exhaust plume of kerosene liquid-oxygen (LOX) motors used by Atlas-type rockets. Once formed, carbon may contribute a continuum-like feature to the optical radiation of a rocket exhaust plume, especially in the near-UV [1]. A carbon monoxide–oxygen chemiluminescence mechanism may also be a source of radiation for the Atlas propellant because carbon dioxide is a large plume exhaust species and atomic oxygen is formed in the shear layer of the plume where the ambient oxygen molecules are dissociated [2]. Such optical interference effects lead to an increased background radiation level for the seeker in all spectral bands, but are most problematical in the infrared. Sensor confusion may also be caused by deliberate countermeasures. Therefore, multi-spectral imaging is important for ground-based imagery for optical signature characterization and onboard seekers.

One approach for multi-spectral imaging uses an imaging spectrometer that acquires images in many contiguous spectral bands simultaneously over a given spectral range. By adding wavelength to the image as a third dimension, the spectrum of any pixel in the scene can be calculated. These images can be used to obtain the spectrum for each image pixel, which can identify components in the target. The most common method of image spectroscopy is changing fixed dichroic filters. Existing systems suffer from large size and weight and operate slowly (approximately a millisecond). Several tunable filters have been proposed, but they all have severe problems. For example, the acousto-optic tunable filter is power-hungry (in kilowatts), while the liquid crystal tunable filter is slow (approximately tens of milliseconds for nematic liquid crystals) and has low efficiency.

The Advanced Technology Branch at SSC San Diego and the Jet Propulsion Laboratory (JPL) have been developing a novel technology that can be applied to BMDO's needs for multi-spectral imaging. The surface plasmon tunable filter (SPTF) described in this paper uses color-selective absorption by a surface plasmon at a metal-dielectric interface to achieve its optical selectivity. If an electro-optic (EO) material is used, an applied voltage can control the resonant frequency of the surface plasmon, and an electrically tunable color filter is formed [3, 4, 5, and 6]. The technology may replace discrete filters and allow for multi-spectral or hyperspectral imaging with a single filter/camera system. This feature is particularly important if minimal payload weight and volume is desired for imager or seeker systems on rockets or missiles.

SURFACE PLASMON TUNABLE FILTER

The surface plasmon (SP) has been studied since the 1960s. It is a collective oscillation in electron density at the interface of a metal and a dielectric [7]. At SP resonance, the reflected light vanishes. This resonance is attenuated total reflection and depends on the dielectric constants of the metal and the dielectric. If an EO material is used as the dielectric and a voltage is applied to change the SP resonance condition, the reflected light can be modulated [8 and 9]. Using this principle, an SP spatial laser light modulator with a contrast ratio greater than 100 has been reported [10]. If we consider the SP light modulator in frequency space, the photons at the SP resonance frequency will be absorbed by the free electrons in the metal, and the photons away from the SP resonance will be totally reflected. If a voltage is applied to the EO material, the resonance frequency will change, and a tunable filter is formed. The SP tunable notch filter was invented based on this voltage-induced color-selective absorption [11 and 12]. Figure 1 schematically shows a reflective-mode SPTF.

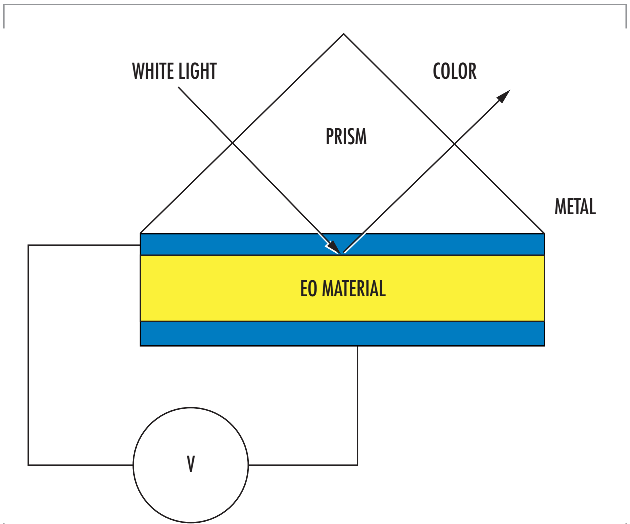

FIGURE 1. Reflective SPTF.

The structure of the SPTF in Figure 1 shows white light incident on the metal-EO interface using a high-index prism (SF57 glass) for coupling. The color of the reflected light is determined by the SP resonance that is a function of the dielectric properties of the materials. Using a thin (55-nm) layer of silver and a liquid crystal (Merck E49) as the EO material, a narrowband SP resonance is obtained (Figure 2). Note that as the applied voltage is increased from 0 to 30 V, the SP absorption shifts from red to violet.

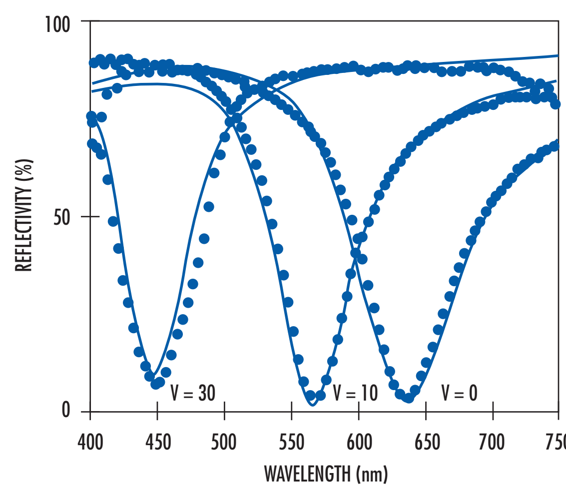

FIGURE 2. SPTF reflection spectra.

Figure 3 shows a symmetric geometry of metal/EO/metal used to form a transmissive filter. Two high-index glass prisms are used for the coupling with a thin metal film evaporated on each prism, and an EO material sandwiched between the two prisms. The thickness of EO material layer is less than 1 wavelength. When an SP wave is excited on one side of the metal/EO material interface by the incident photons, the energy of the resonance photons convert into the motion of free electrons of the metal film. The optical field penetrates the thin EO layer and excites another SP wave with the same frequency at the other EO/metal interface because of the symmetric structure. The resonance photons will then re-radiate out as transmitted light. When a voltage is applied to the EO material, the index of the EO material changes, leading to a change of the SP resonance frequency and the transmission spectrum. Theoretical calculation shows that for two silver films separated by a 150-nm EO material layer (Merck E49), a change in the index of the EO layer from 1.5 to 2.0 leads to transmission peak shifts from 450 to 650 nm.

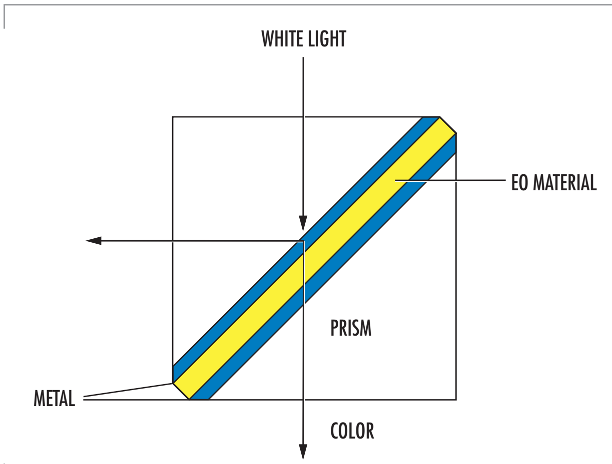

FIGURE 3. Transmissive SPTF.

Varying the thickness of the dielectric layer between the two metal films can also change the coupling mechanics. Using a symmetric geometry similar to what was used in Figure 3, a SPTF can be constructed using a changeable air gap to select the spectrum. Figure 4 shows the theoretical calculation of reflectivity vs. wavelength of the Air Gap SPTF and its effective tuning ability. Using silver as the metal films, when the thickness of the air gap changes from 300 to 5000 nm, the peak transmission shifts from 400 to 1600 nm. Though the structure of the Air Gap SPTF is schematically similar to the Fabry-Perot filter, the physics is totally different. The photons are incident at an angle greater than the critical angle, and two metal films must be used to generate the SP resonance. Furthermore, the tunable range runs from 400 to 1600 nm and is not limited by 2X as the Fabry-Perot filter requires. The SPTF can also be configured to operate based on angle of incidence [13].

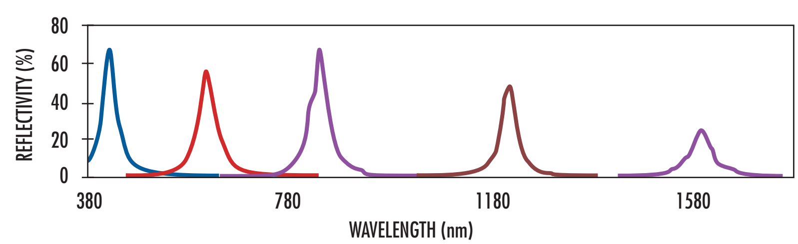

FIGURE 4. Tuning of the Air Gap SPTF.

FUTURE ADVANCES

A major advantage of SPFT technology is the ability to integrate it with various optical sensors and detectors. These products include state-of-the-art miniature photo-multiplier tubes available commercially (e.g., Hamamatsu R5600), microelectronic photo-multipliers [14 and 15], and solid-state detectors such as charge-coupled devices (CCDs) and active pixel sensors [16]. Compared with an acoustic-optic tunable filter and liquid crystal tunable filter, the SPTF is lightweight, low-power, and works in a wide temperature range. If the glass material is chosen so that its thermal expansion matches the thermal expansion of the EO material, this device works in a wide temperature range (-200 to +200°C. Though liquid crystal material was used in these experiments, the liquid crystal material can be replaced by solid-state EO materials such as potassium di-hydrogen phosphate (KDP), potassium titanyl phosphate (KTP), ethylene oxide (EO) polymers, organic crystals, and organic salts. If a solid-state material is used, the SP modulator can reach very fast (less than 1-μs) modulation speeds. Materials optimized for near-infrared (IR) and mid-IR can also optimize the device for specific applications. Such devices can be used for multi-spectral and hyperspectral imaging, for chemical analysis, and in surveillance and reconnaissance.

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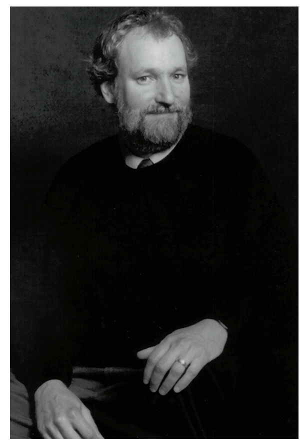

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REFERENCES

1. Levin, D. A. 1997. "Modeling of Optical Target Characterization from High Temperature Hypersonic Flows," unpublished proposal.
2. Slack, M. and A. Grillo. 1985. "High Temperature Rate Coefficient Measurements of CO+O Chemiluminescence," *Combustion and Flame*, vol. 59, p. 189.
3. Wang, Y. 1995. "Voltage-Induced Color-Selective Absorption with Surface Plasmons," *Applied Physics Letters*, vol. 67, p. 2759.
4. Wang, Y., S. D. Russell, and R. L. Shimabukuro. 1997. "Surface Plasmon Tunable Filter and Spectrometer-on-a-Chip," *Proceedings of SPIE*, vol. 3118, p. 288.
5. Wang, Y., S. D. Russell, and R. L. Shimabukuro. 1998. "Electronically Tunable Mirror with Surface Plasmons," *Proceedings of SPIE*, vol. 3292, p. 103.
6. Wang, Y. 1977. "Electronically Tunable Color Filter with Surface Plasmon Waves," *Proceedings of SPIE*, vol. 3013, p. 224.
7. Raether, H. 1980. *Excitation of Plasmons and Interband Transitions by Electrons*, monograph in series: *Springer Tracts in Modern Physics*, vol. 88, Springer-Verlag, Berlin, Germany.
8. Wang, Y. and H. J. Simon. 1993. "Electrooptic Reflection with Surface Plasmons," *Optical and Quantum Electronics*, vol. 25, p. S925.

9. Schildkraut, J. S. 1988. "Long-Range Surface Plasmon Electrooptic Modulator," *Applied Optics*, vol. 20, p. 1491.
10. Caldwell, M. E. and E. M. Yeatman. 1992. "Surface Plasmon Spatial Light Modulators Based on Liquid Crystal," *Applied Optics*, vol. 31, p. 3880.
11. Wang, Y. 1996. "Surface Plasmon High Efficiency HDTV Projector," U.S. Patent #5,570,139.
12. Russell, S. D., R. L. Shimabukuro, and Y. Wang. 1998. "Transmissive Surface Plasmon Light Valve," U.S. Patent #6,122,091.
13. Ramirez, A. D., S. D. Russell, and R. L. Shimabukuro. "Resonance Tunable Optical Filter," Patent Pending, Navy Case No. 79,095.
14. Shimabukuro, R. L. and S. D. Russell. 1993. "Microelectronic Photomultiplier Device with Integrated Circuitry," U.S. Patent #5,264,693.
15. Shimabukuro, R. L. and S. D. Russell. 1994. "Multilayer Microelectronic Photo-multiplier Device," U.S. Patent #5,306,904.
16. Fossum, E. R. 1995. "Low Power Camera-on-a-Chip Using CMOS Active Pixel Sensor Technology," *1995 Symposium on Low Power Electronics*, 9 to 10 October, San Jose, CA.

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